The Doppler Method, or Radial Velocity Detection of Planets:

I. Technique

1. Keplerian Orbits
2. Spectrographs/Doppler shifts
3. Precise Radial Velocity measurements

Star Wobble

Segment 1

Ben Simons

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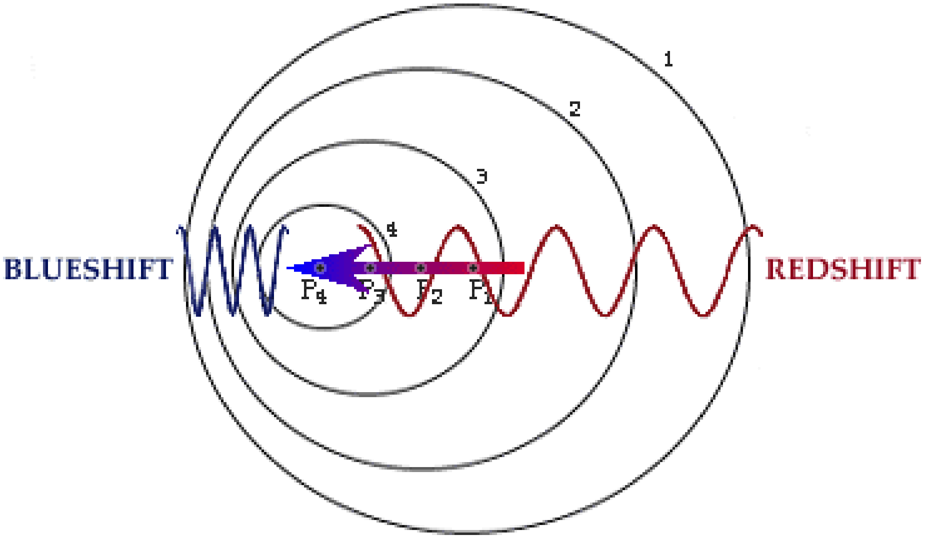
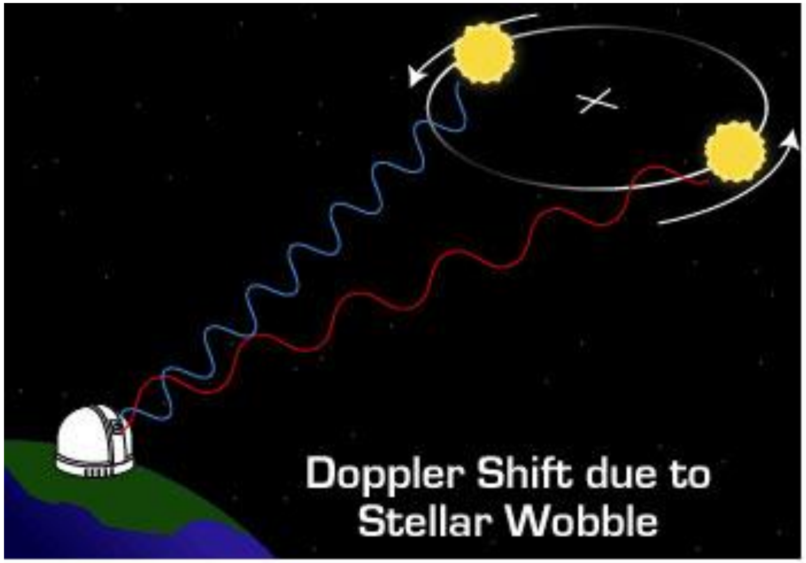
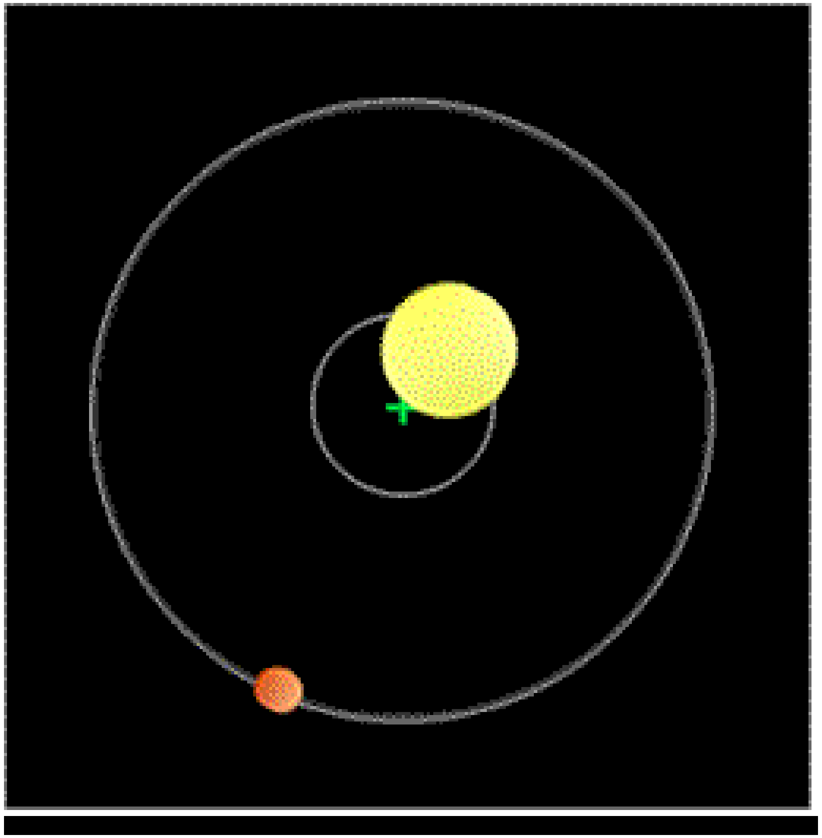
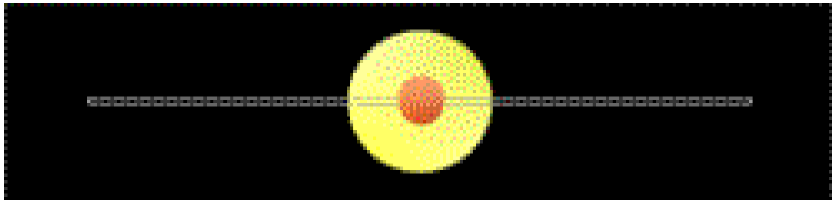
The Doppler Effect:

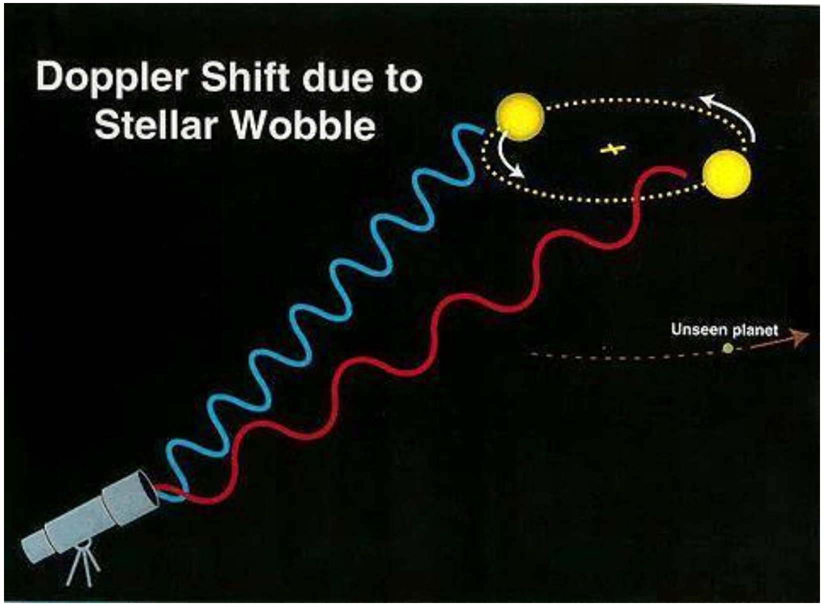




The “Radial Velocity” Technique:



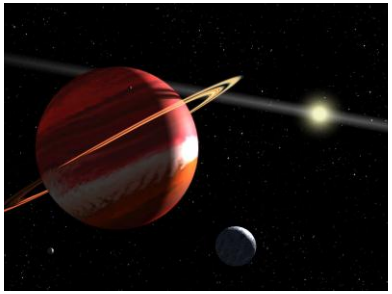




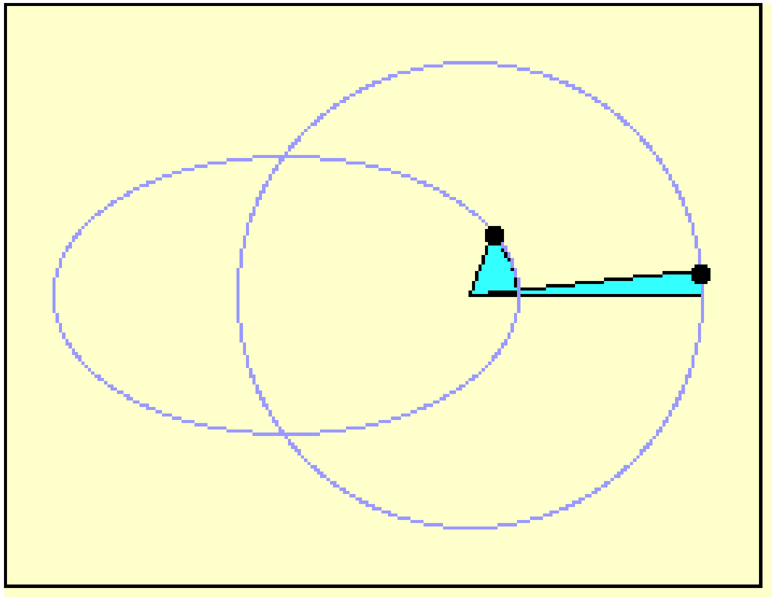
Johannes Kepler's uphill battle

Johannes Kepler

(1571-1630)

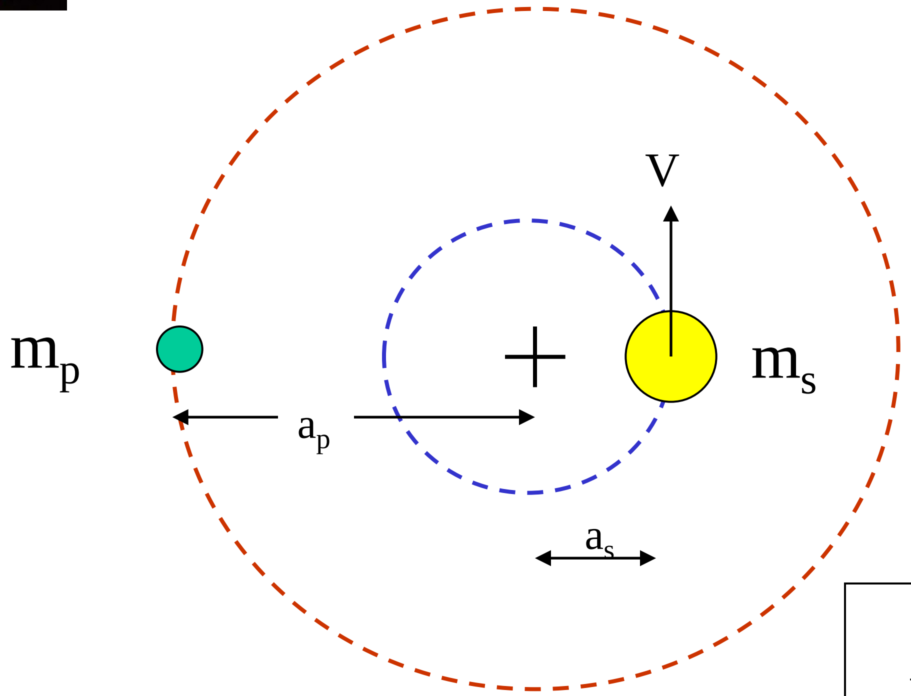


Three laws of planetary motion:



1. Planets move in ellipses with the Sun in on focus
2. The radius vector describes equal areas in equal times
3. The squares of the periods are to each other as the cubes of the mean distances

Newton‘s form of Kepler‘s Law



$$\boxed{V_{obs} = \frac{28.4\ \ m_p \sin i}{P^{1/3} m_s^{2/3}}}$$

Approximations:

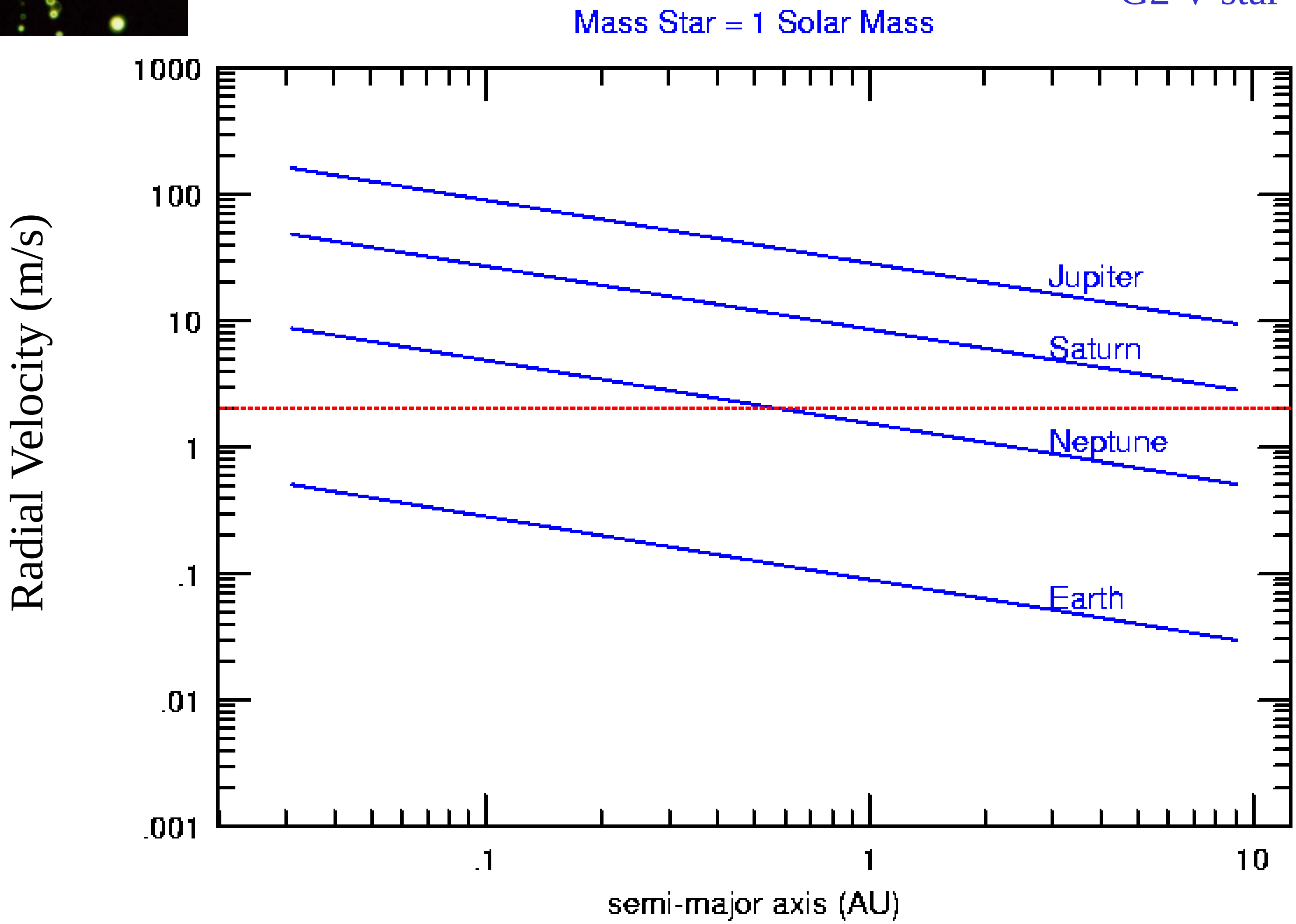
m_s » m_p

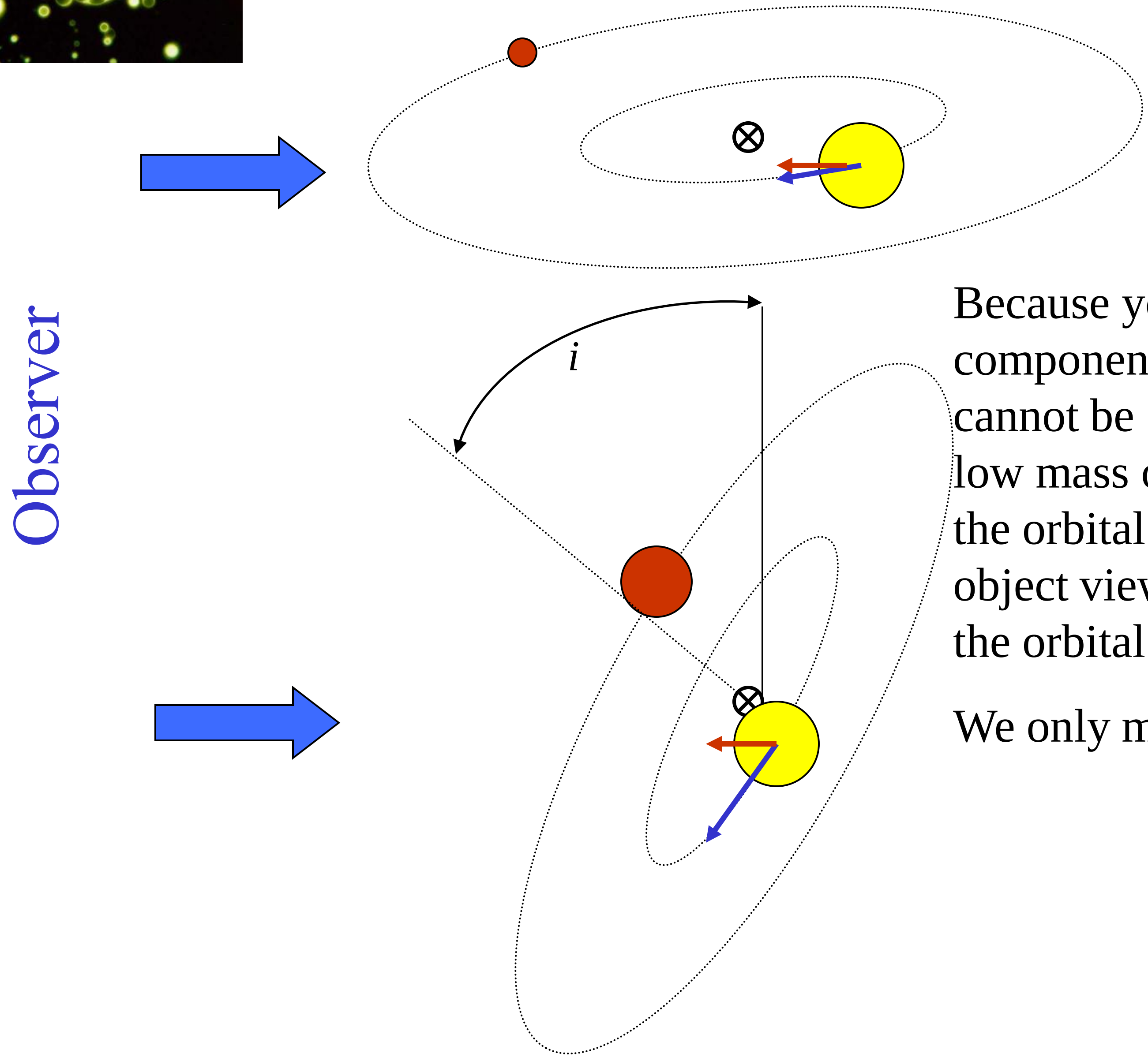
Radial Velocity Amplitude of Sun due to Planets in the Solar System

Planet	Mass (M_J)	V($\mathrm{m\ s^{-1}}$)
Mercury	1.74×10^{-4}	0.008
Venus	2.56×10^{-3}	0.086
Earth	3.15×10^{-3}	0.089
Mars	3.38×10^{-4}	0.008
Jupiter	1.0	12.4
Saturn	0.299	2.75
Uranus	0.046	0.297
Neptune	0.054	0.281
Pluto	1.74×10^{-4}	3×10^{-5}

Radial Velocity Amplitude of Planets at Different *a*

G2 V star

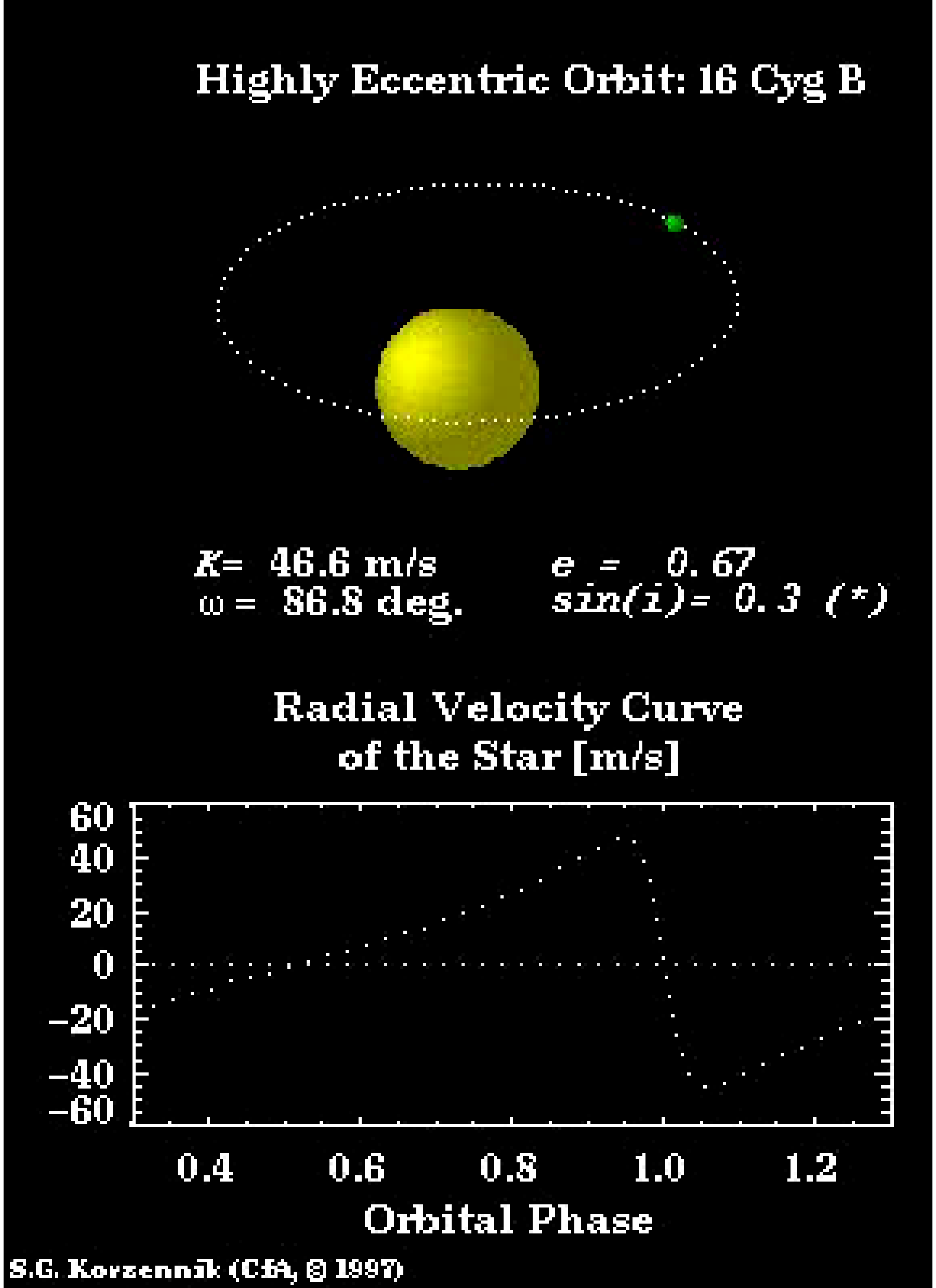




Because you measure the radial component of the velocity you cannot be sure you are detecting a low mass object viewed almost in the orbital plane, or a high mass object viewed perpendicular to the orbital plane

We only measure **M_{Planet} x sin *i***

ASTs309L



Highly Eccentric Orbit: 16 Cyg B

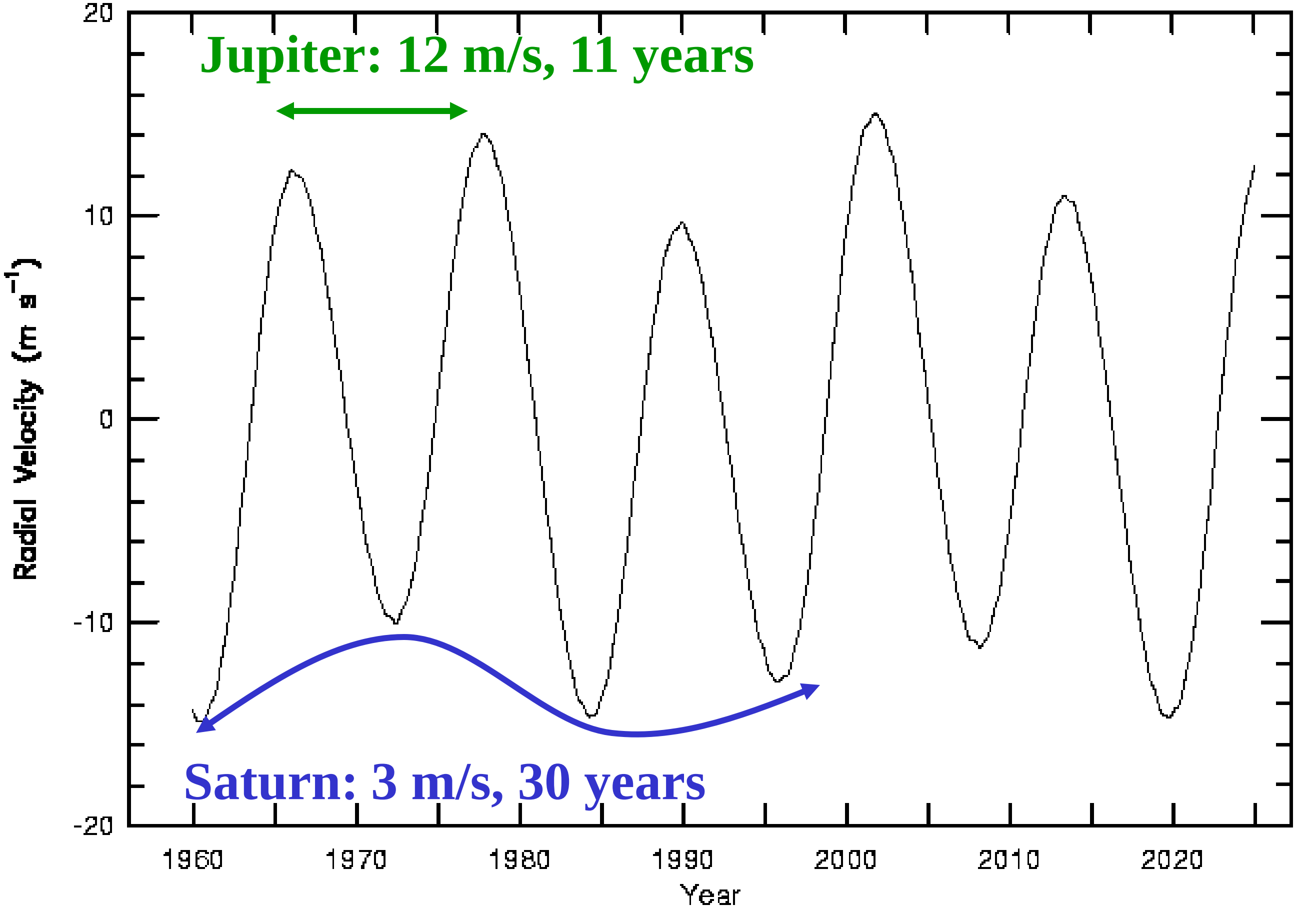
S.G. Korzennik (CfA, © 1997)

Radial Velocity measurements

Requirements:

- Precision of better than 10 m/s
- Stability for at least 10 Years

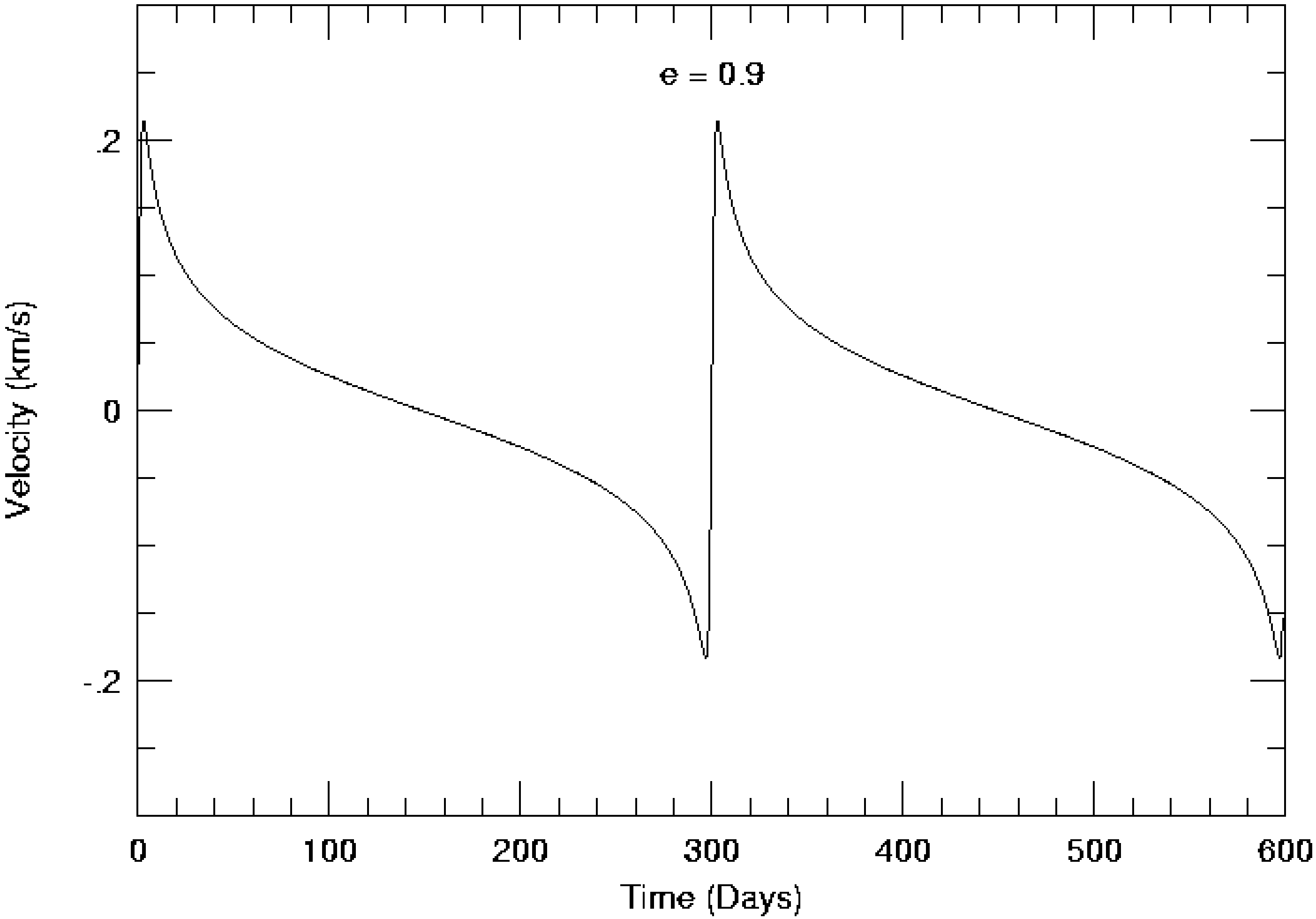
$$V_{obs} = \frac{28.4 \;\; m_p \sin i}{P^{1/3} m_s^{2/3}}$$



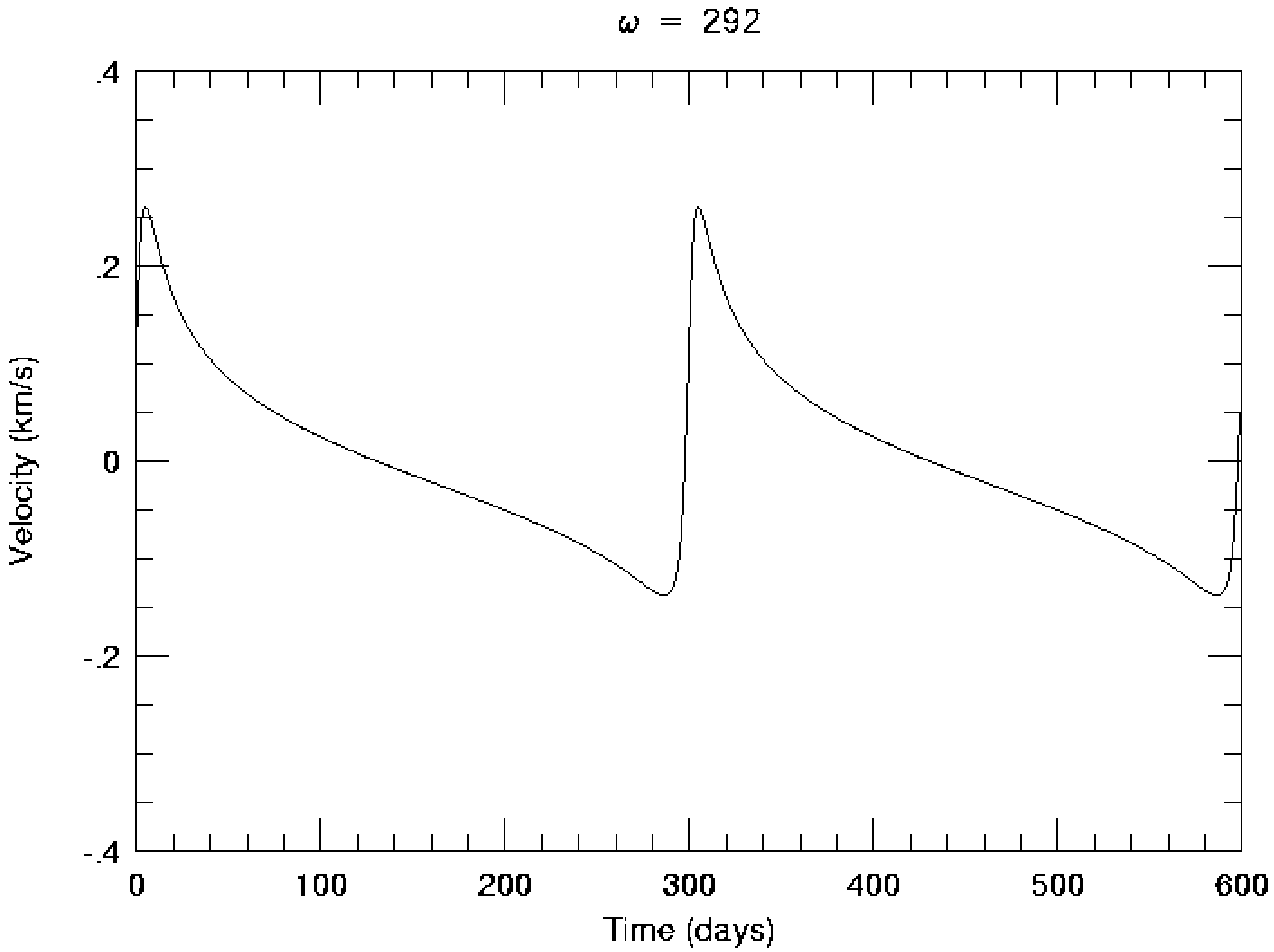
Jupiter: 12 m/s, 11 years

Saturn: 3 m/s, 30 years

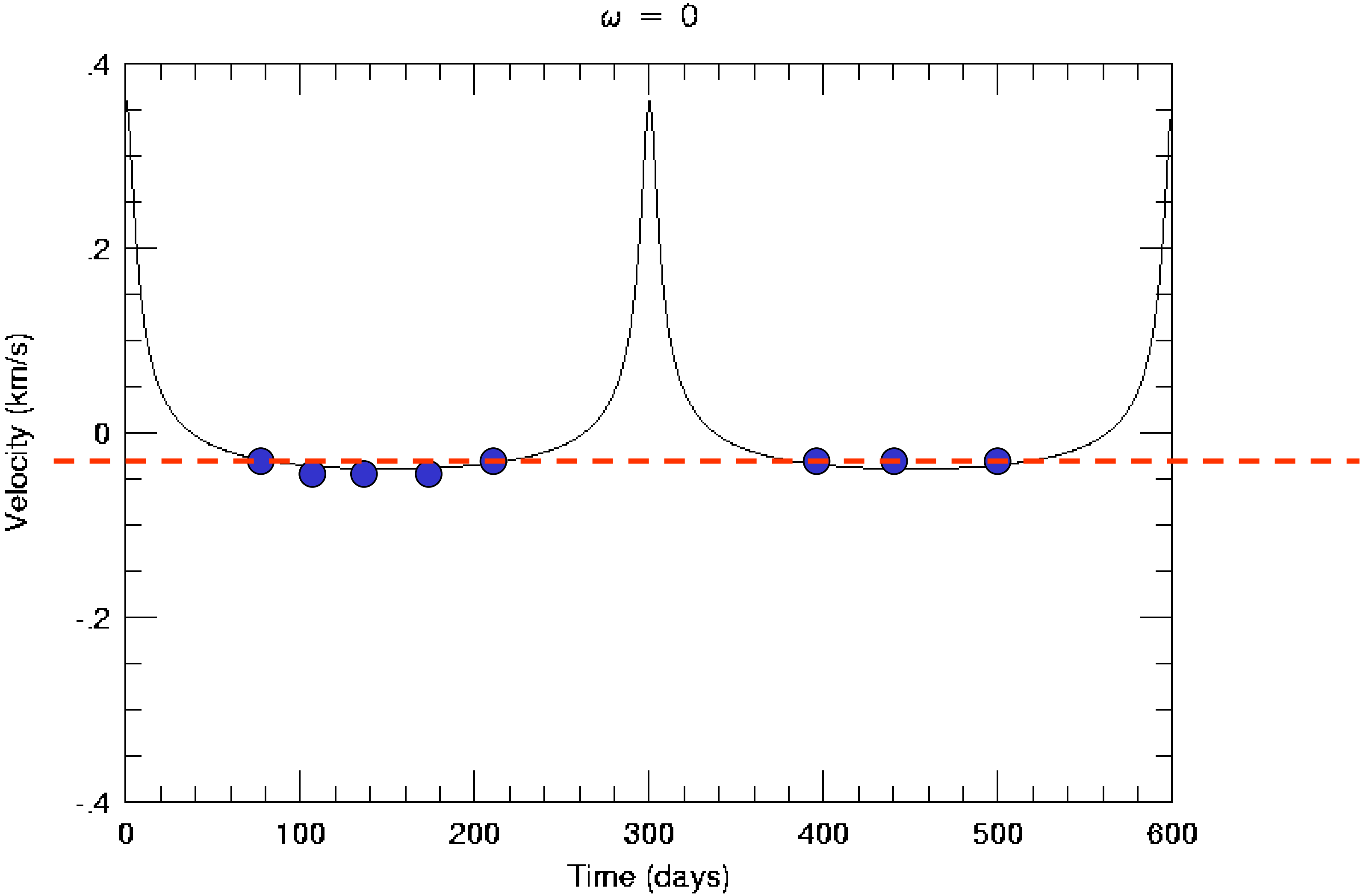
Radial velocity shape as a function of eccentricity:



Radial velocity shape as a function of ω, e = 0.7 :



Eccentric orbit can sometimes escape detection:



With poor sampling this star would be considered constant

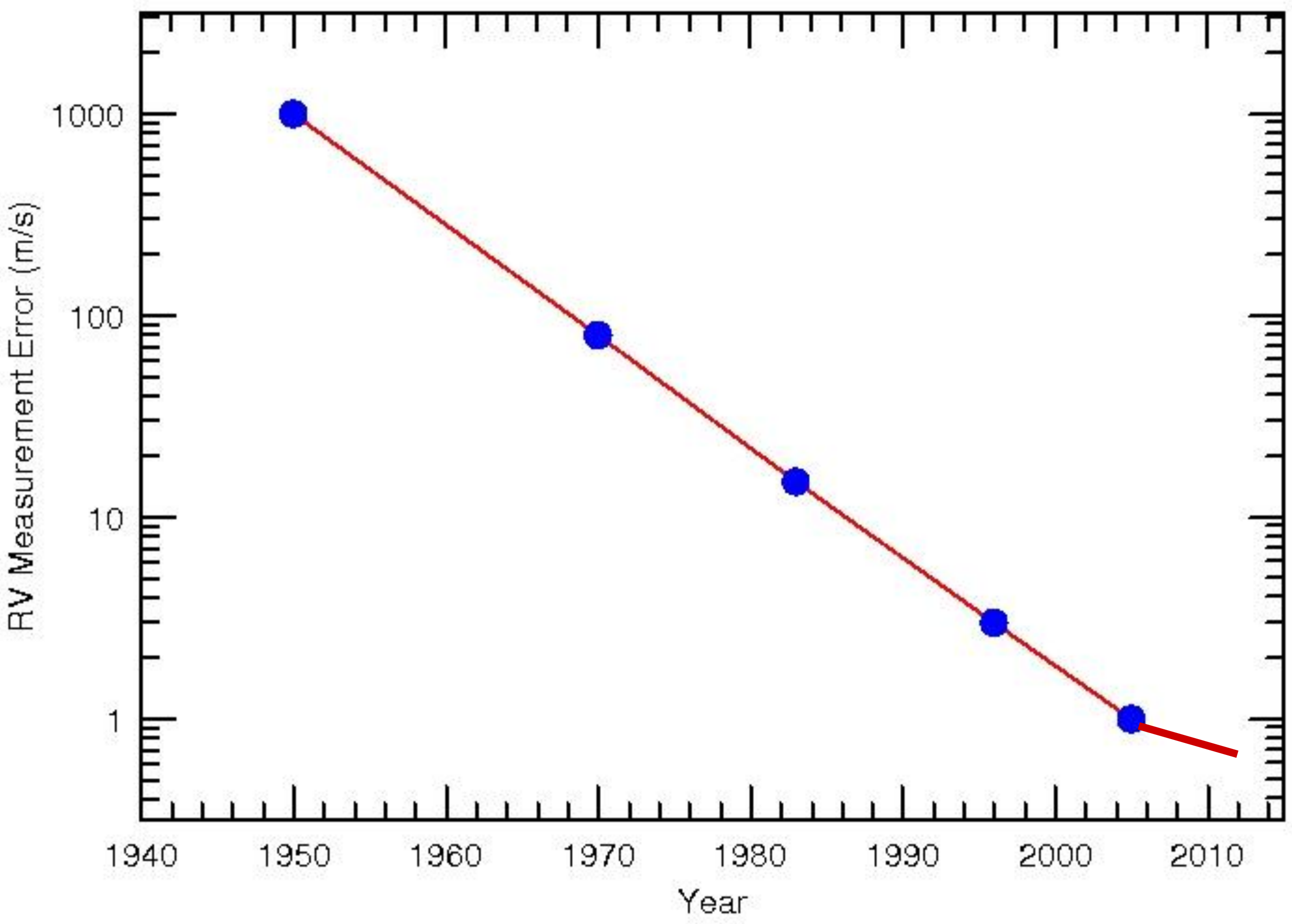
Measurement of Doppler Shifts

In the non-relativistic case:

$$\frac{\lambda - \lambda_0}{\lambda_0} = \frac{\Delta v}{c}$$

We measure Δv by measuring $\Delta\lambda$

The Radial Velocity Measurement Error with Time



How did we accomplish this?

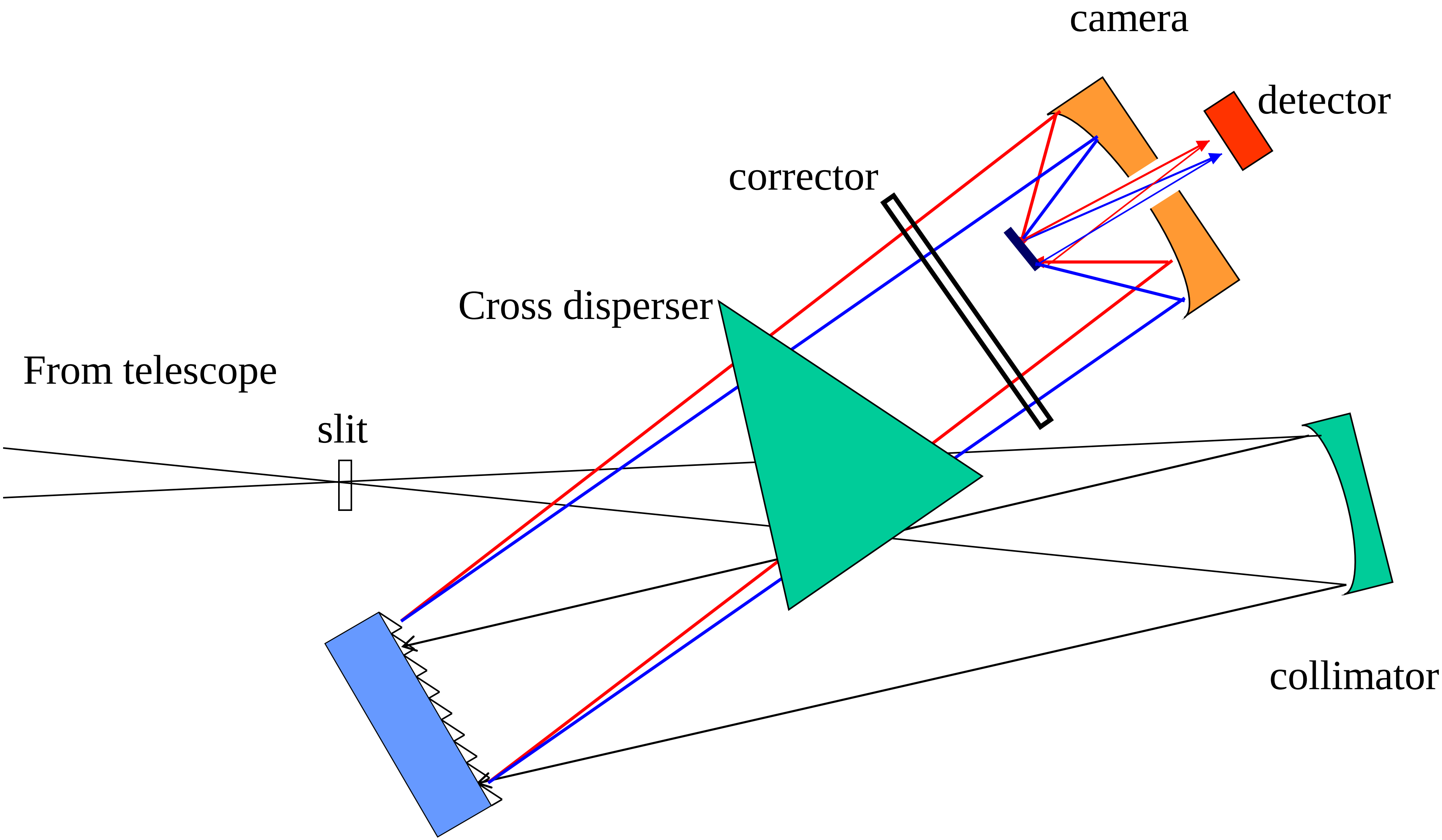
The Answer:

1. Electronic Detectors (CCDs)
2. Large wavelength Coverage Spectrographs
3. Simultaneous Wavelength Calibration (minimize instrumental effects)
4. Fast Computers...

Instrumentation for Doppler Measurements

High Resolution Spectrographs with Large Wavelength Coverage

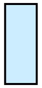
Echelle Spectrographs



A spectrograph is just a camera which produces an image of the slit at the detector. The dispersing element produces images as a function of wavelength

slit

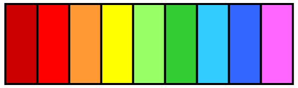
▯



without disperser

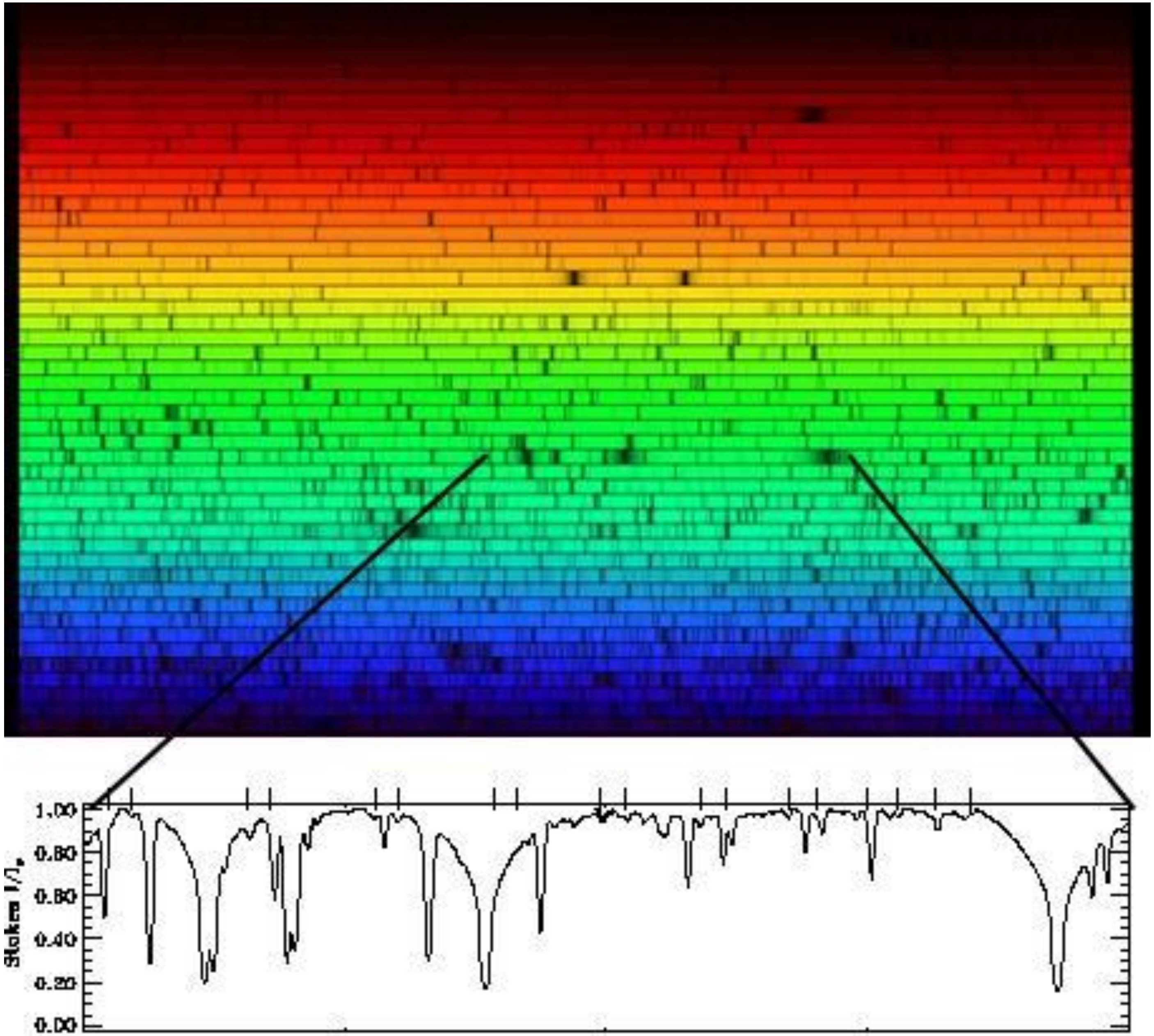
slit

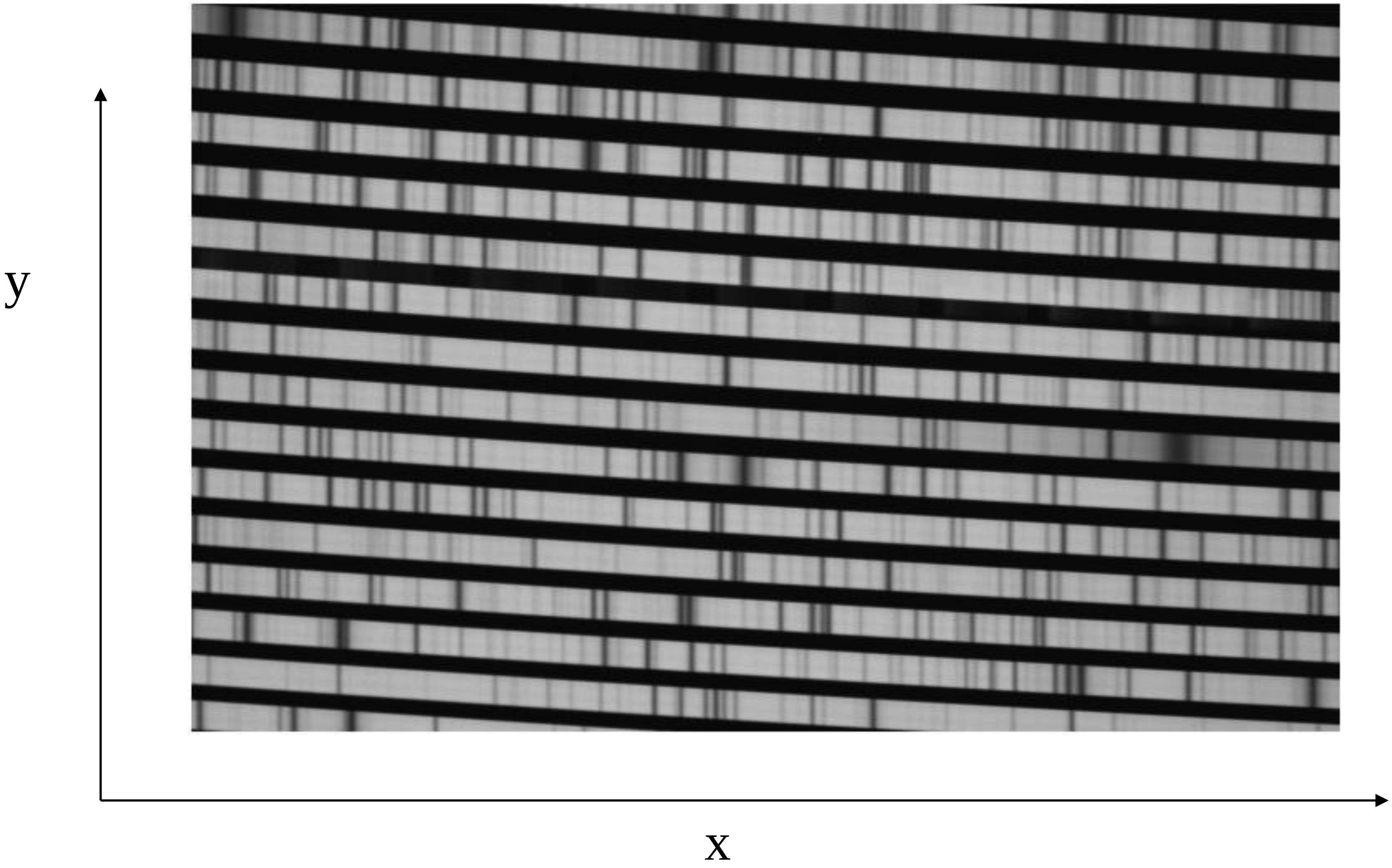
▯



with disperser

A Spectrum Of A Star:





On a detector we only measure x- and y- positions, there is no information about wavelength. For this we need a calibration source

CCD detectors only give you x- and y- position. A doppler shift of spectral lines will appear as Δx

$$\Delta x \rightarrow \Delta\lambda \rightarrow \Delta v$$

How large is Δx ?

			For Δv = 20 m/s	
R	Ang/pixel	Velocity per pixel (m/s)	Δpixel	Shift in mm
500 000	0.005	300	0.06	0.001
200 000	0.125	750	0.027	4×10^{-4}
100 000	0.025	1500	0.0133	2×10^{-4}
50 000	0.050	3000	0.0067	10^{-4}
25 000	0.10	6000	0.033	5×10^{-5}
10 000	0.25	15000	0.00133	2×10^{-5}
5 000	0.5	30000	6.6×10^{-4}	10^{-5}
1 000	2.5	150000	1.3×10^{-4}	2×10^{-6}

So, one should use high resolution spectrographs….up to a point

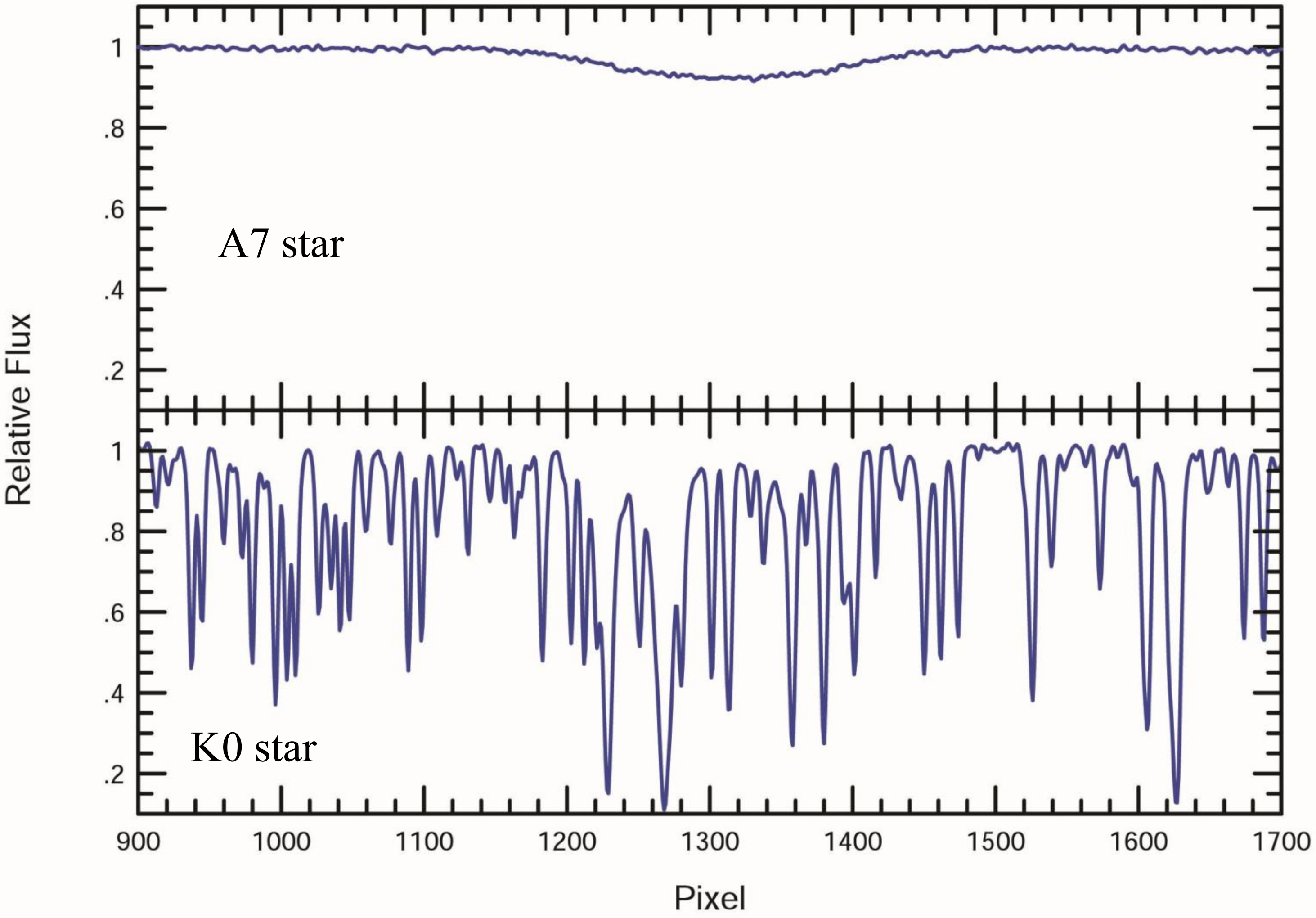
How does the RV precision depend on the properties of your spectrograph?

The Radial Velocity precision depends not only on the properties of the spectrograph but also on the properties of the star.

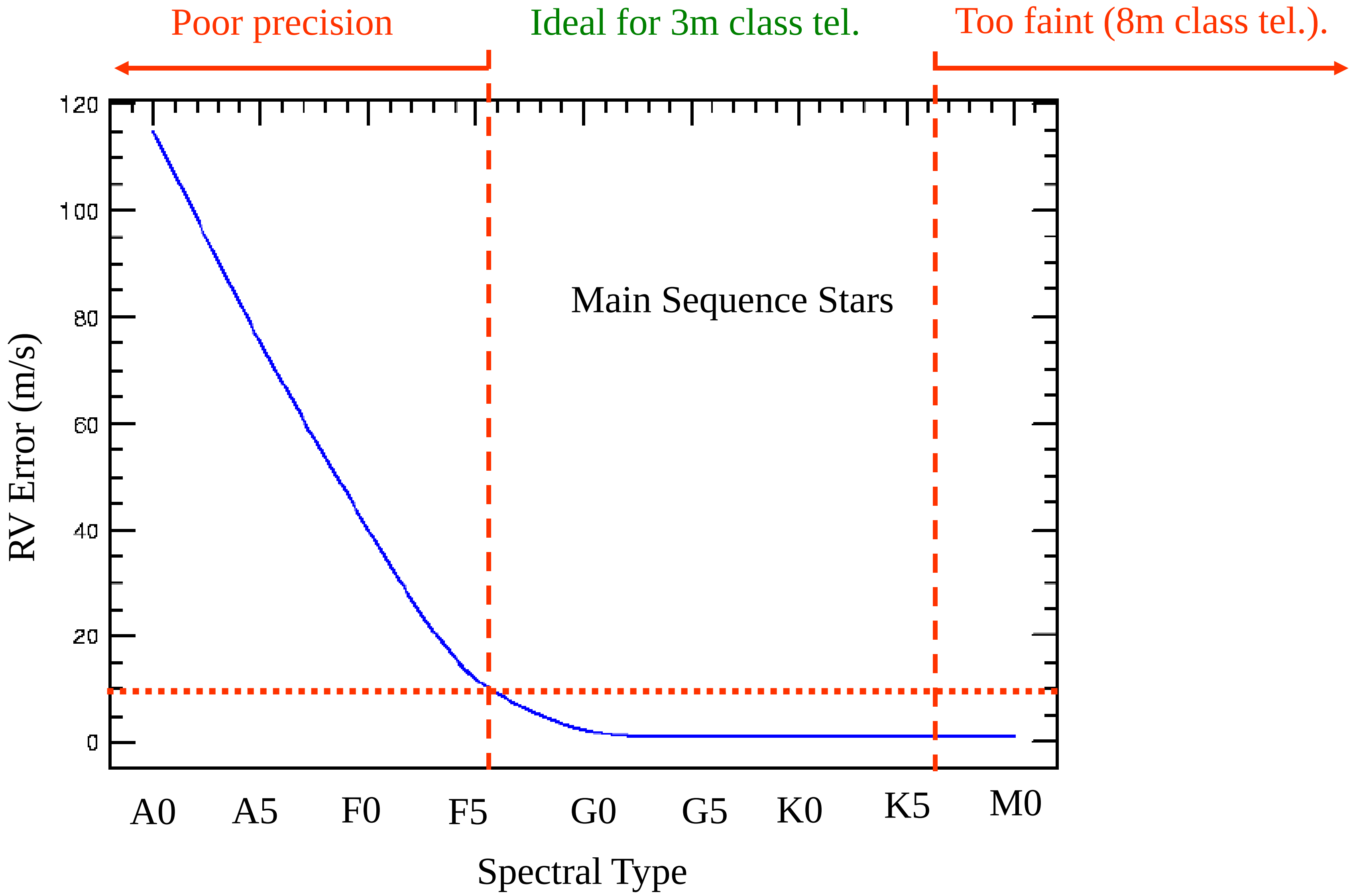
Good RV precision → cool stars of spectral type later than F6

Poor RV precision → hot stars of spectral type earlier than F6

Why?



Early-type stars have few spectral lines (high effective temperatures) and high rotation rates.



98% of known exoplanets are found around stars with spectral types later than F6

Eliminate Instrumental Shifts

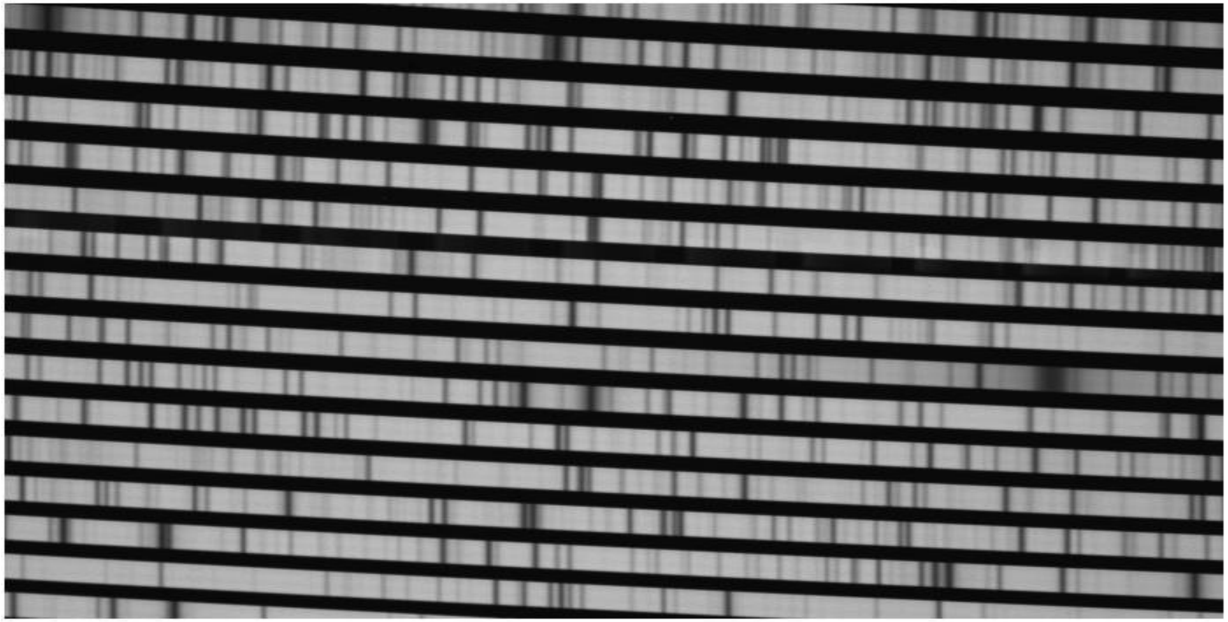
Recall that on a spectrograph we only measure a Doppler shift in Δx (pixels).

This has to be converted into a wavelength to get the radial velocity shift.

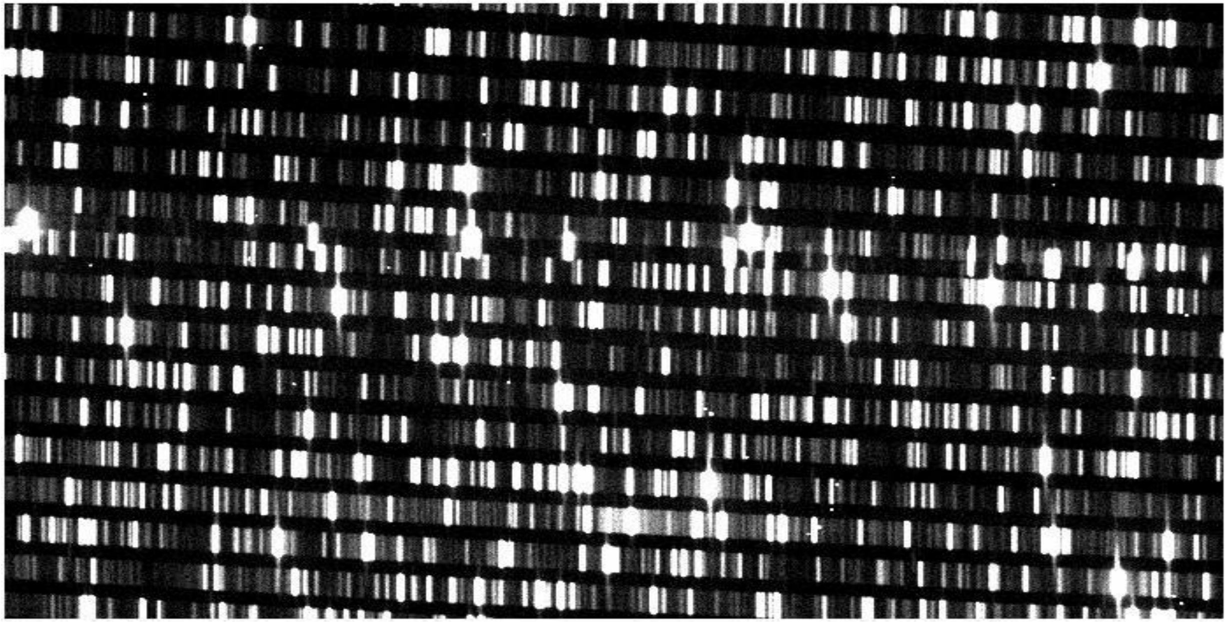
Instrumental shifts (shifts of the detector and/or optics) can introduce „Doppler shifts“ larger than the ones due to the stellar motion

Traditional method:

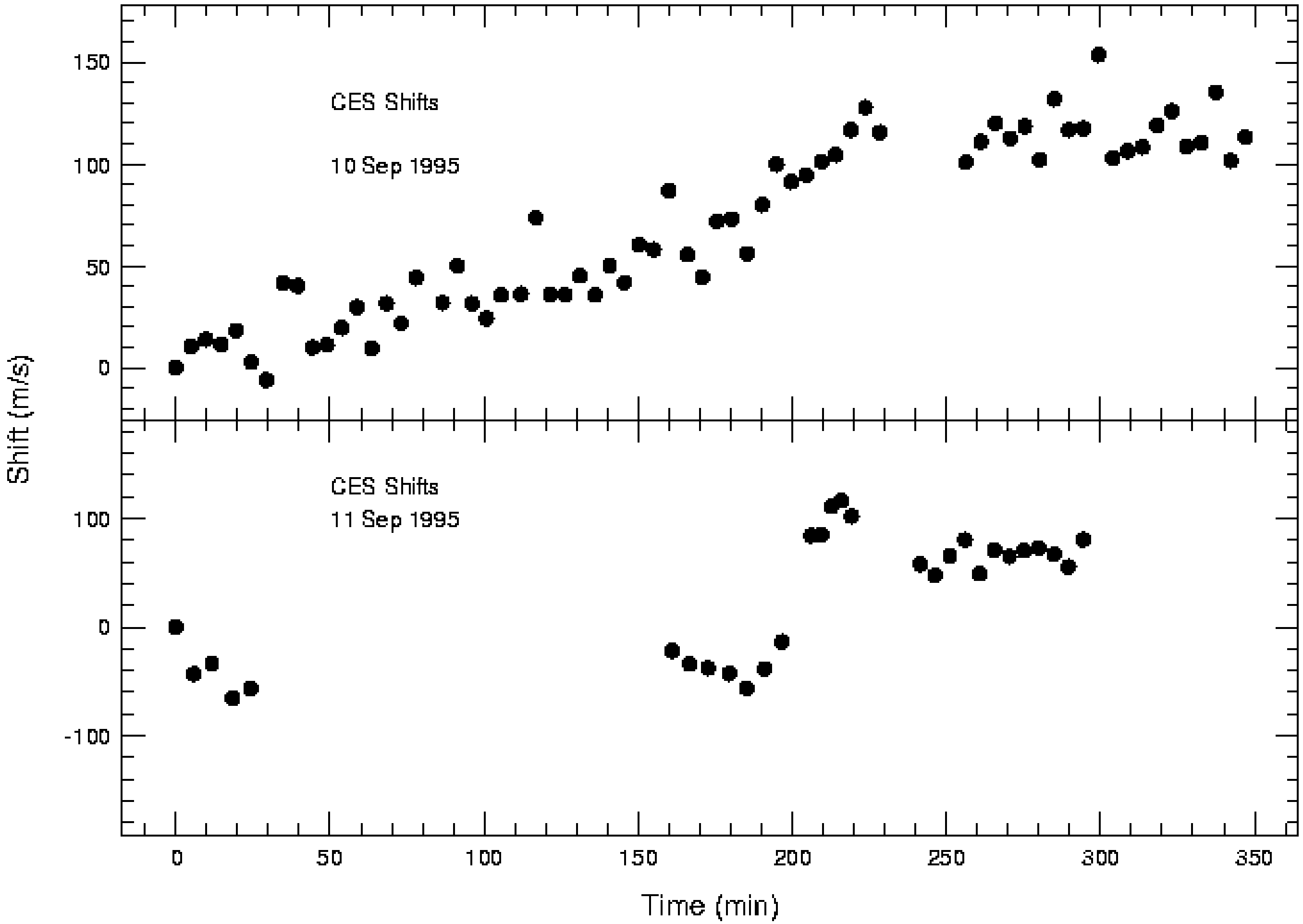
Observe your star→



Then your calibration source→

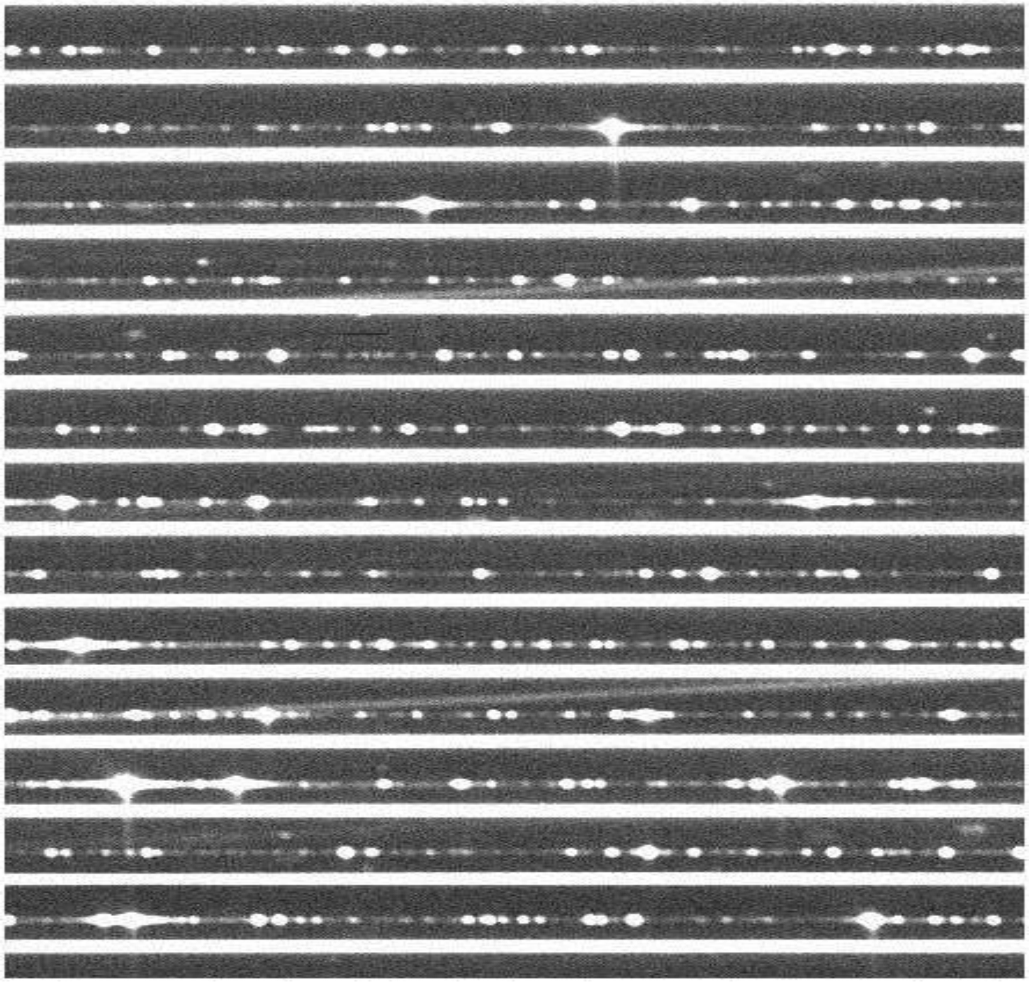


Problem: these are not taken at the same time…



... Short term shifts of the spectrograph can limit precision to several hunrdreds of m/s

Solution 1: Observe your calibration source (Th-Ar) simultaneously to your data:



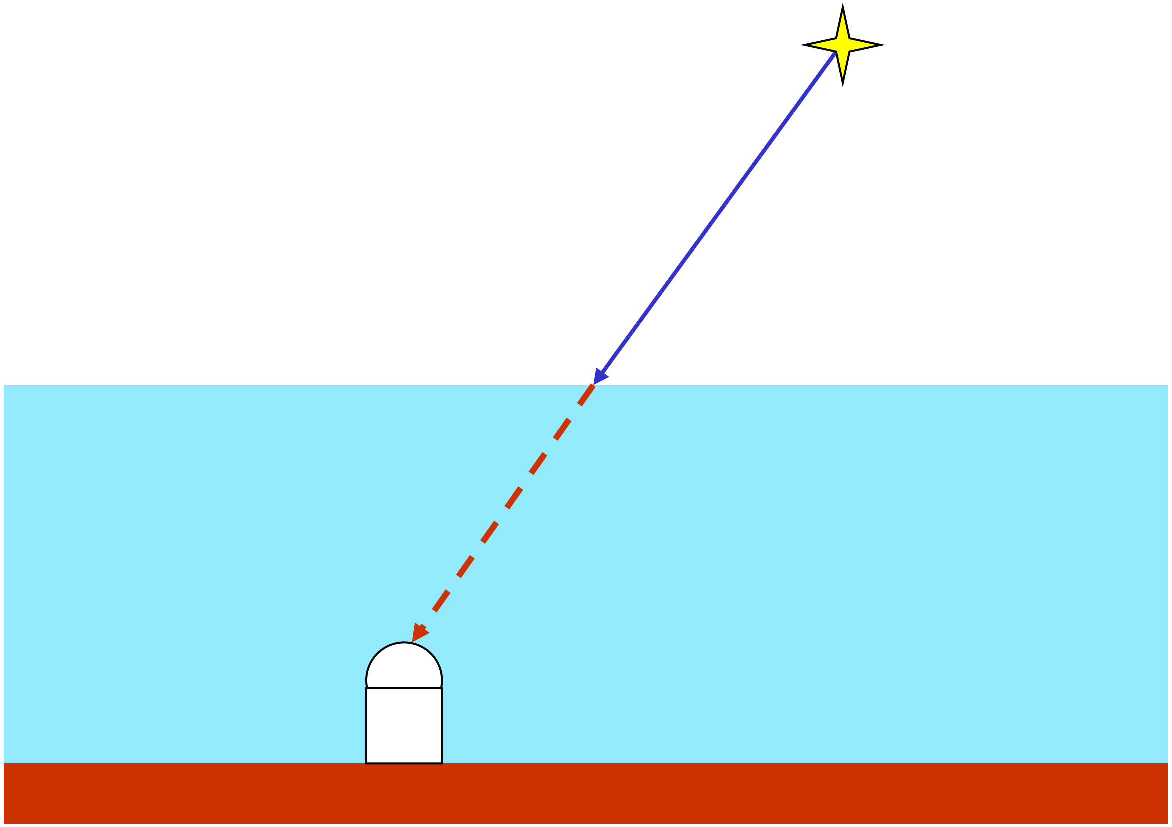
Stellar spectrum

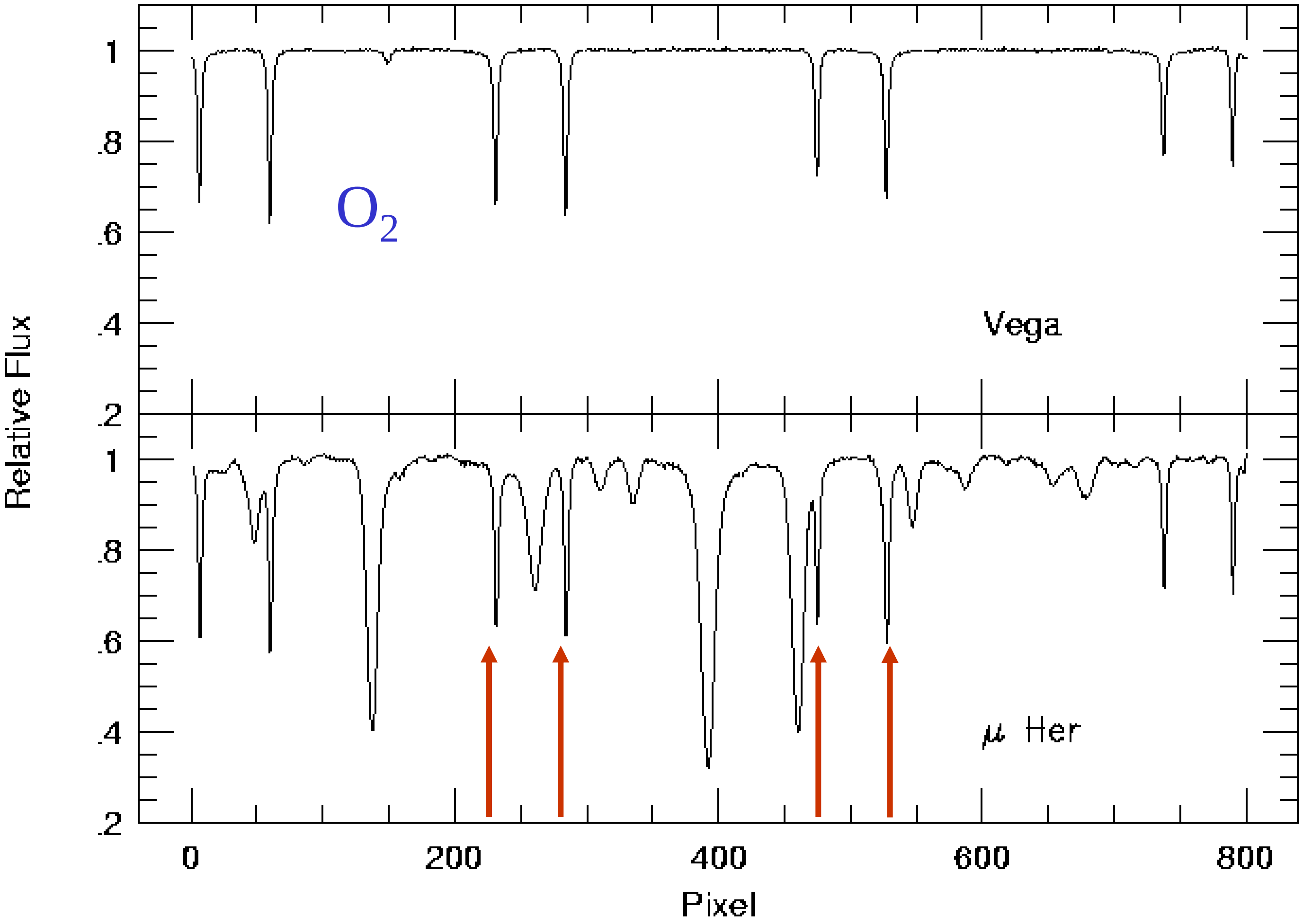
Thorium-Argon calibration

Spectrographs: CORALIE, ELODIE, HARPS

Solution 2: Absorption cell

a) Griffin and Griffin: Use the Earth‘s atmosphere:





6300 Angstroms

Example: The companion to HD 114762 using the telluric method. Best precision is 15–30 m/s

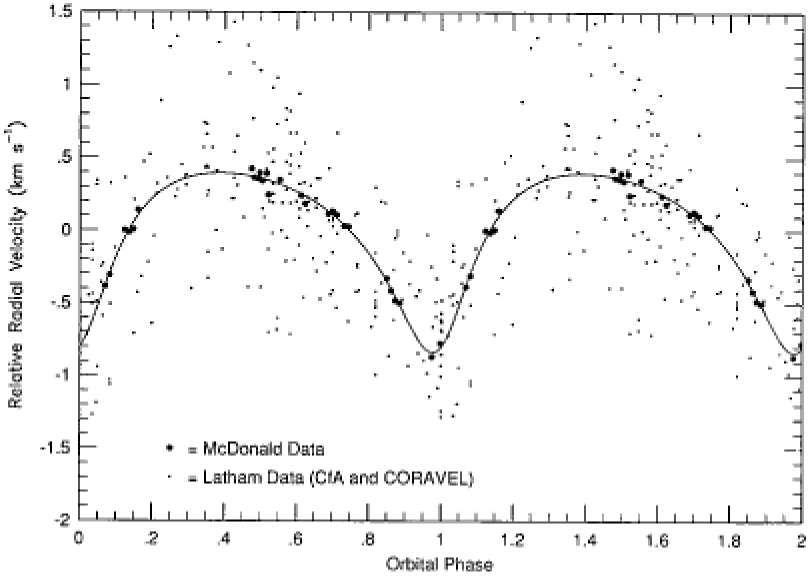


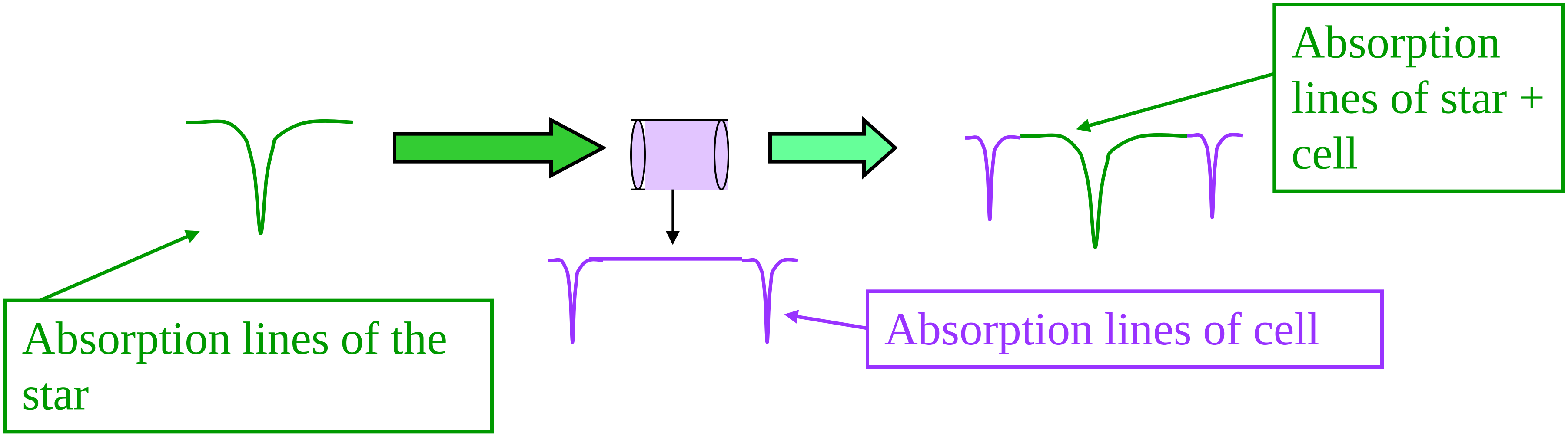
FIG. 1.—Radial velocity curve for HD 114762. The McDonald data presented in this paper are shown as large filled circles. The original discovery data of Latham et al. (1989) are shown as small dots. The solid curve is from the orbital solution derived from the McDonald data.

Filled circles are data taken at McDonald Observatory using the telluric lines at 6300 Ang.

Limitations of the telluric technique:

- Limited wavelength range (≈ 10s Angstroms)
- Pressure, temperature variations in the Earth‘s atmosphere
- Winds
- Line depths of telluric lines vary with air mass
- Cannot observe a star without telluric lines which is needed in the reduction process.

b) Use a „controlled“ absorption cell



Absorption lines of star + cell

Absorption lines of the star

Absorption lines of cell

Campbell & Walker: Hydrogen Fluoride (HF) cell:

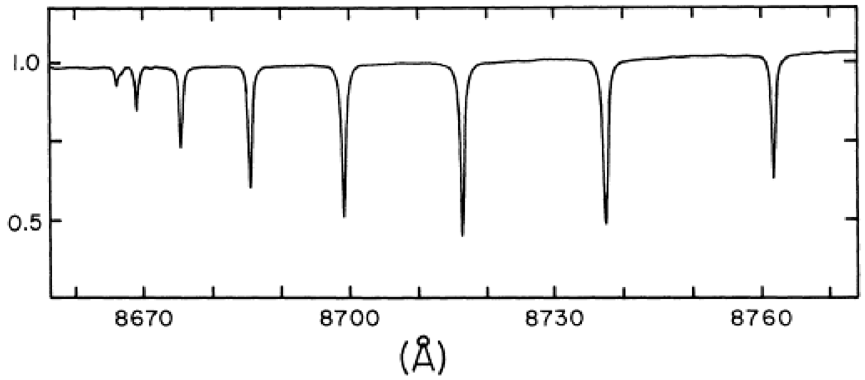


FIG. 1—Absorption spectrum of hydrogen fluoride 3–0 band *R* branch.

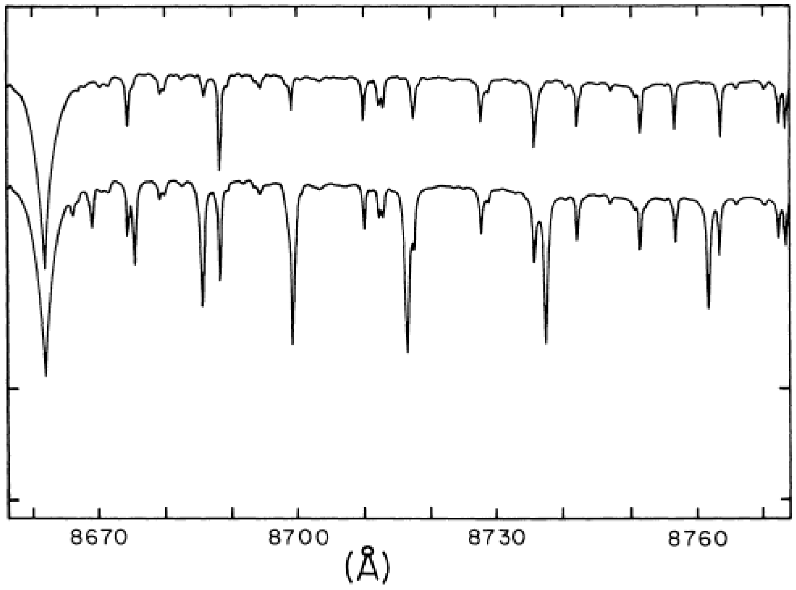


FIG. 3—Solar spectra with (*lower*) and without (*upper*) the hydrogen fluoride lines. The strong line at left is Ca II λ8662.

Drawbacks:

- Limited wavelength range (≈ 100 A)
- Temperature stablized at 100 C
- Long path length (1m)
- Has to be refilled every observing run
- **Dangerous**

Demonstrated radial velocity precision of 13 m s^{-1} in 1980!

A better idea: Iodine cell (first proposed by Beckers in 1979 for solar studies)

Spectrum of iodine

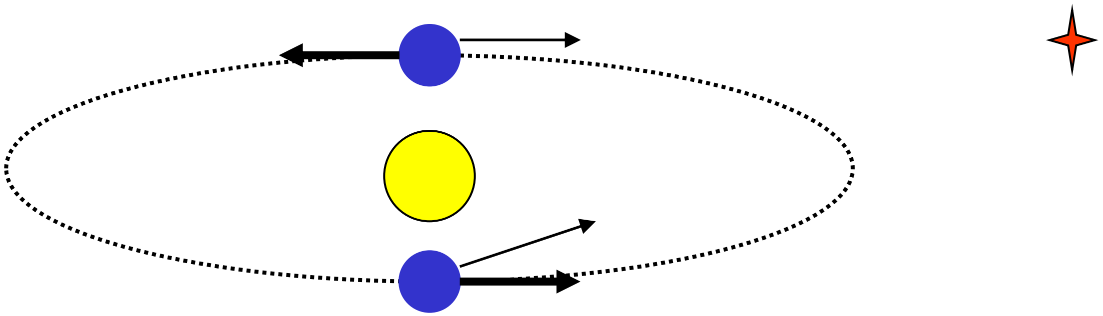
Advantages over HF:

- 1000 Angstroms of coverage
- Stablized at 50–75 C
- Short path length (≈ 10 cm)
- Can model instrumental profile
- Cell is always sealed and used for >10 years
- If cell breaks you will not die!

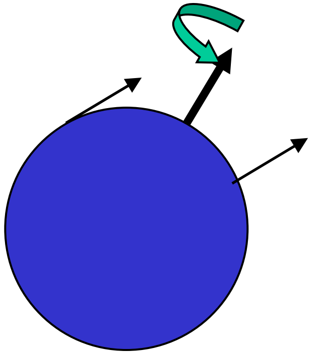
HARPS

Simultaneous ThAr cannot model the IP. One has to stabilize the entire spectrograph

Barycentric Correction



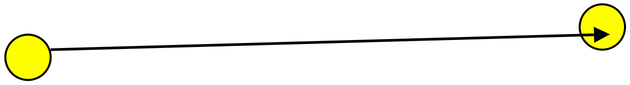
Earth’s orbital motion can contribute ± 30 km/s (maximum)



Earth’s rotation can contribute ± 460 m/s (maximum)

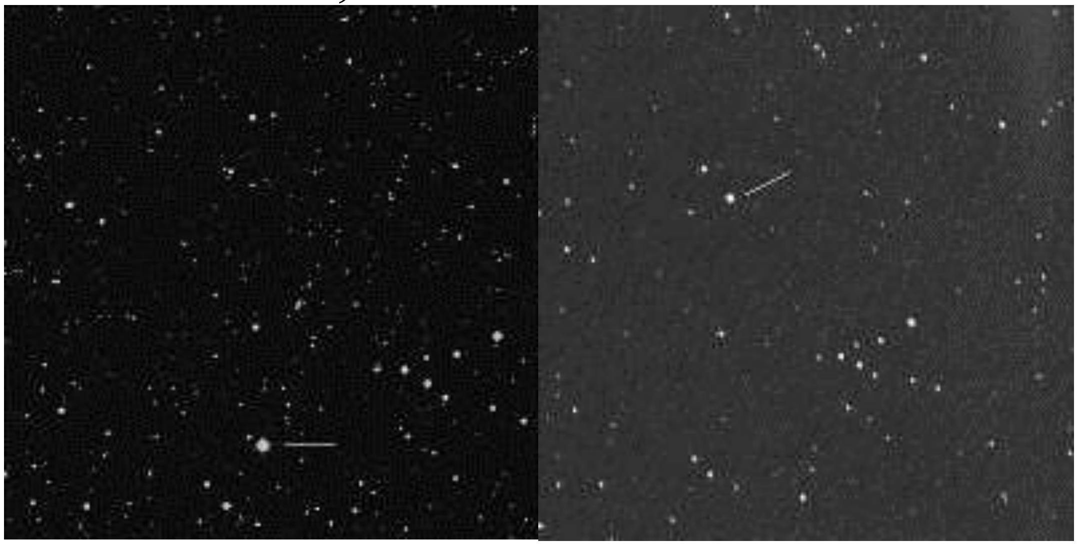
Needed for Correct Barycentric Corrections:

- Accurate coordinates of observatory
- Distance of observatory to Earth‘s center (altitude)
- Accurate position of stars, including proper motion:



α', δ'

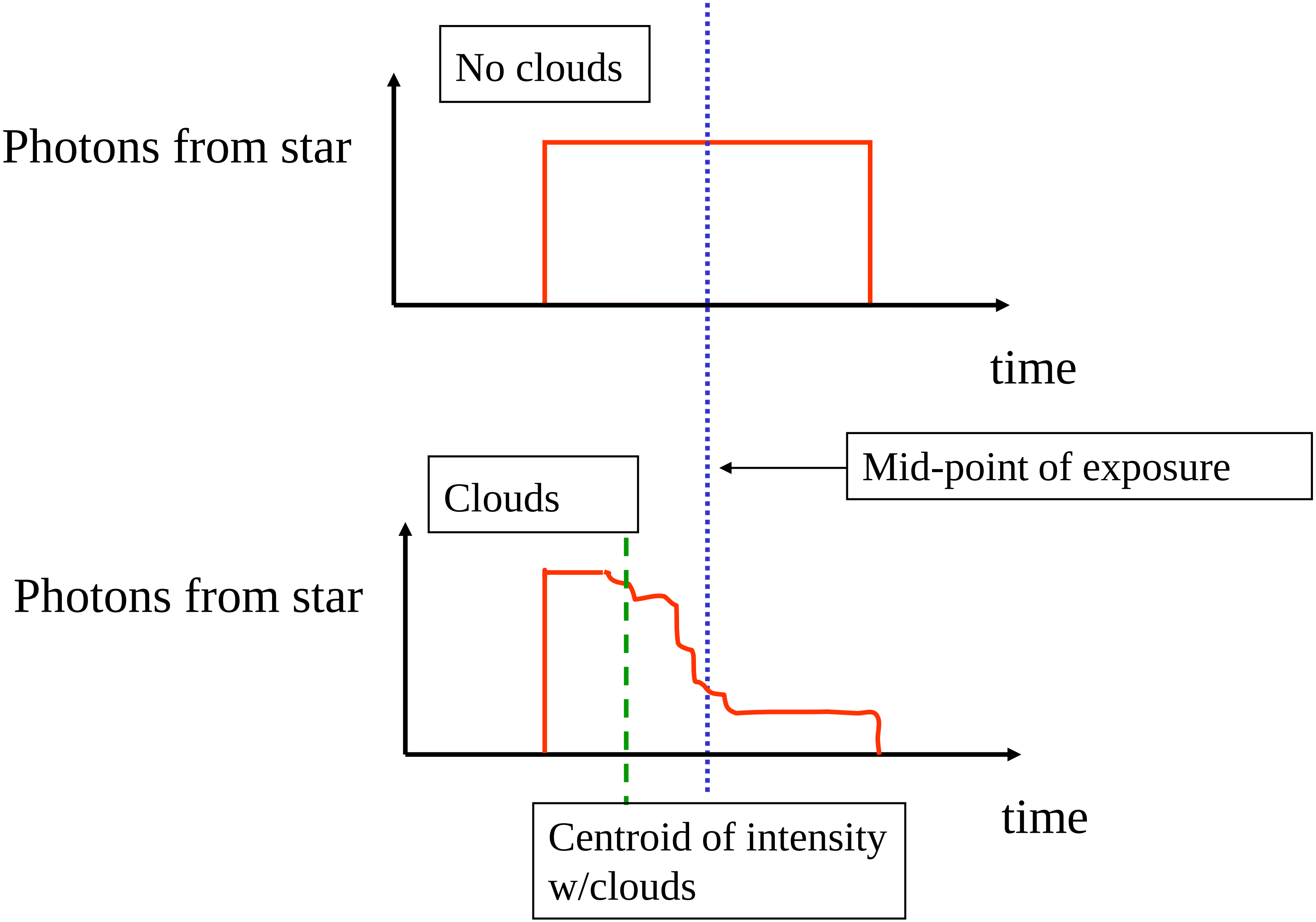
α, δ



Worst case
Scenario:
Barnard‘s star

Most programs use the JPL Ephemeris which provides barycentric corrections to a few cm/s

For highest precision an exposure meter is required



No clouds

Photons from star

time

Mid-point of exposure

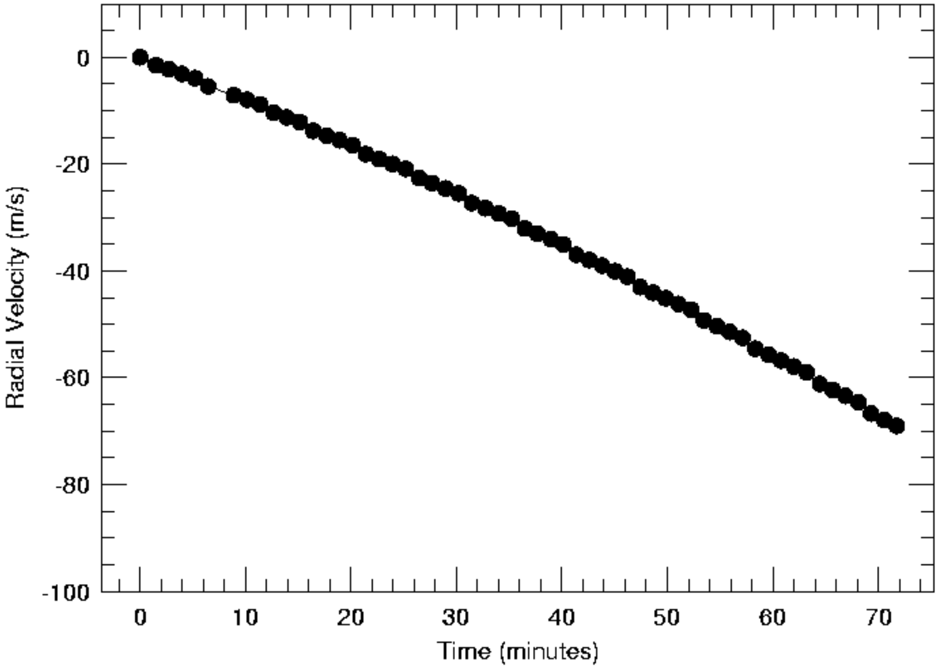
Clouds

Photons from star

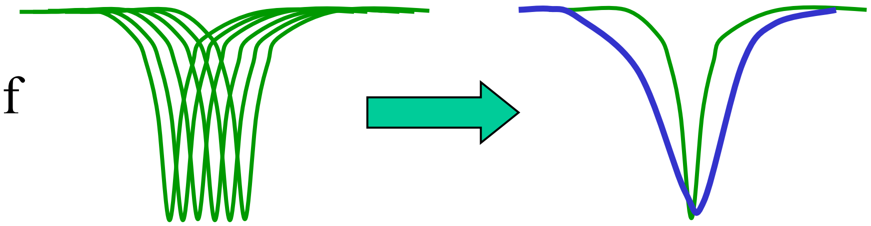
time

Centroid of intensity w/clouds

Differential Earth Velocity:



Causes „smearing“ of spectral lines



Keep exposure times < 20-30 min